Navigating through the Venus Atmosphere

S. Kuen Wong[1], Tung-Han You[2], Jon D, Giorgini[3],
Lily Lim[4], Pam Chadbourne[5]

Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, California 91109

The orbit of the Magellan spacecraft was circularized by aerobraking between 25 May 1993 and 3 August 1993. During the 70 days, a small aerodynamic drag was applied to the 729 orbits to accomplish a 540 x 197 km near circular orbit, Since the Magellan spacecraft was not design for aerobraking and this is the first-ever int.erplanetary aerobraking, this procedure was very challenging for the Magellan Flight Teams. This paper presents the problems and challenges of the Magellan Navigation Team, The challenges are:

1. to predict the periapsis time to an accuracy of less than 100 seconds
2. to accurately predict the dynamic pressure incurred by the spacecraft,
3. to model and to generate this predictions in a timely manner.
4. to provide navigation support 7 days per week for 70 days with 3 navigators and one graphic specialist to generate daily package for presentation and display,

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1 Magellan Navigation Team Chief, Navigation Systems Section
2 Magellan Navigation Team member, Navigation Systems Section
3 Magellan Navigation Team member, Navigation Systems Section
4 Magellan Navigation Team member, Navigation Systems Section
5 Magellan Navigation Team member, Martin Marietta Co.

The problems encountered by the Navigation Team in order to meet the above challenges are:

1. The uncertainty in the Venus atmosphere model,
2. The uncertainty in the Venus gravity model.
3. The uncertainty in predicting the attitude control thruster firing,
4. The sparse amount of radiometric tracking data,
5. The radiometric data editing is complicated by the effects of the Venus atmosphere fluctuations,

Brief **Aerobraking Mission Description**

On 25 May 1993 the periapsis altitude of the Magellan orbit was lowered from 171.36 km to 149.25 km with an Orbit Trim Maneuver (OTM3). The 0TM3 was followed with three walkin OTMS between 26 May and 29 May 1993 to lowered the periapsis altitude to 141.13 km and dynamic pressure ($1/2\rho v^2$) of 0.23 Newton/meter2. This dynamic pressure is a little outside the aerobraking corridor (0.27-0.32 N/m^2), but having 3 extra days to examine the behavior of the Venus atmosphere at the beginning of aerobraking is useful. There were 6 up-otms during June, and 3 down-otm in July to maintain the dynamic pressure on spacecraft within the corridor. The up-otms are maneuver to raise the periapse altitude and the down-otm are maneuver to lower the periapse altitude. When the apoapsis altitude of the Magellan orbit got down to 54) km, the spacecraft exit aerobraking with two otm on 3 August 1993 to raise the periapsis altitude to 163.29 km from 135.30 km, On 5 August the periapsis altitude was raise to 197 km with 3 otms completing an 541 km x 197 km orbit and the start of gravity data gathering,

Venus Atmosphere Model

Magellan Navigation uses an exponential model to represent the Venus atmosphere. The density p is a function of both altitude and time.

$$\rho_j = \rho_{ij} \exp[(h_{ij} - h)/H_{ij}]$$

where, hi = the reference altitudes (km).

ρ_{ij} = the atmosphere density at altitude hi and time t_j (gm/cm^3).

t_j = the reference epochs either absolute time or local solar time.

H_{ij} = the exponential scale height at time t_j for the ith layer of the atmosphere (km).

h = the spacecraft altitude (km),

t = the current epoch.

We used the scale height driven model, the densities ρ_{ij} are computed from the input scale heights. The scale heights and density for multilayers and local solar time are from the Venus International Reference Atmosphere (VIRA) model provided by G. M, Keating in 22 April 1993. There were two models provided: one assumed for single C02 and the other was assumed double C02 .The single C02 model are listed in Table 1 and 2. The double C02 model was recommend by Gerry Keating for Magellan project to use. The scale height for each layer was computed from the densities at each layer to insure continuity at layer boundaries.

An assumed atmospheric variability of 15%(1-sigma) before 5 pm local solar and 50°/0 after 5 pm along with the spacecraft temperature constraint was used in determining the location of aerobraking corridor,

Venus Gravity Model

The Pre-aerobrake covariance and simulation studies indicated that. mismodeling of the Venus gravitational field would be the dominent error source in Magellan orbit determination and prediction errors, Members of the Magellan Navigation Team processed Doppler tracking data from the Pioneer Venus Orbiter (PVO) spacecraft and selected Magellan tracking from Cycles 1,2, and 3 to produce new Venus harmonic gravity field complete to degree and order 21 in order to improve Magellan orbit determination and prediction accuracies. This updated model is designated MGN5 Venus Gravity Model,

There is another model from Gravity Investigator Group, PMGNF60-50, a

60x60 gravity field (truncated to 50x50) that includes PVO data and Cycle 4 Magellan tracking data through March 28, 1993. This gravity yielded a better 5 day prediction in periapsis time than MGN5, but it requires 3 times as much CPU time to integrate a given trajectory, During aerobraking, the quick turn around of Orbit Determination solution is highly critical, MGN5 gravity model was used for daily orbit. computation and long term predictions. Periapsis altitude plot was generated using the two models over the aerobraking duration, so we know when MGN5 gravity model is slightly deviate from the PMGNF60-50 model.

Attitude Control Thruster Firing

The spacecraft is guided through the drag pass by an on-board attitude profile which strives to keep the vehicle in the most optimum, aft-end first, orientation. When this orientation is perfectly aligned with the velocity vector, the average attitude error is O degree. If the periapsis time data is not accurate then the profile will not orient the spacecraft optimally and resulting in more thruster firing, The ACS thruster control attitude such the angle-of-attack is less than 10 degrees. These thruster firing can be represented by delta V (velocity change) and we do not know when the thruster is fired but it is between exit periapsis and approximately 600 second later, A history of the delta V per orbit. for the aerobraking duration is shown in Fig. 1.

DSN Radiometric Tracking Data

The orbit. profiles for day of aerobraking 1-60 and 60-70 are given in Fig.2 and Fig3. Only when the spacecraft is on HGA (high gain antenna) and MGA (medium gain antenna) and during the OTM block when there is no OTM are the possible opportunity for tracking data gathering. There is a maximum of 133 minutes of tracking data per orbit (1064 minutes of tracking data per day), However, at the end game (60 days from start. of aerobrake) there is a maximum of 20 minutes per orbit (320 minutes of tracking data per day), The above maximum tracking assume continuous tracking which is not the case. About 1 week into aerobraking, DSS 61 went down with bearing problem and out of commission until after aerobraking.

DSS 61 was one of the stations which Magellan has scheduled heavily for the aerobraking duration.

Navigation Strategy for Aerobraking

The Pre-aerobrake covariance and simulation studies indicated that local gravity field model must be estimated in every OD solution and use for short term prediction in order to bring the periapsis timing error to an acceptable value. The Pre-aerobrake covariance and simulation studies results are given in Tables 3 to 5. The navigation aerobraking strategies are:

1. Start the OD solution with the MGN5 gravity model and estimate an 8x8 local gravity field and use this 8x8 local gravity field along with the higher frequency terms of the MGN5 gravity field to generate short term predictions (<5 days), For prediction (less accurate) longer than 5 day, MGN5 gravity will be used.

2. Estimate for the atmosphere density at every periapsis and use these estimates to update the density predicts, Since we used the scale height driven atmospheric model we are solving for the base density at periapsis altitude of 131 km and the scale height is a function of local solar time. With the base density and scale height for layers from 131 km to 250 km, Density can be computed for any altitude from 131 to 300 km. The layers are 1 km for periapsis altitude 131-151 and 5 km for periapsis altitude 151-250 km. Having the atmosphere density at 131 km for every orbit, the change in the atmosphere density should be a function of local salar time and the trend of these atmosphere densities can easily model for orbit prediction. The knowledge of the atmosphere density which we learn from Magellan Gravity cycle (cycle 4) and the VIRA atmosphere model also help in the atmosphere density prediction.

3. The attitude control thruster firing is modeled by navigation as a constant acceleration for a duration of 600 seconds. The history of small force file(thruster firing) from the spacecraft team is converted into acceleration per orbit, Because the thruster firing duration is offset from the periapsis, it has an effect on both the periapses altitude (dynamic pressure prediction) and periapsis time prediction. These accelerations are also estimated in the OD solution in an attempt to separate gravity, atmosphere and thruster firing, To generate orbit predictions, a prediction of the

thruster firing must be inputed. The average of the recent. history of the thruster firing was used as thruster firing prediction. At times that was not a good prediction.

To input these accelerations were no easy task, because of an OD program limitation, We do not have the capability to input these accelerations as a periapsis relative event, Instead these acceleration times must be inputed as absolute time. For a five day prediction, there are 80 start time and 80 stop time. A member of the Navigation team had to spend time to write a program to automate these inputs, Even then, to generate a predicted trajectory, it required 3 iteration of acceleration times because the periapsis time are changing with these inputs.

The Navigation activities during aerobraking

The navigation team start their day at 7 am when the tracking data, small force file, media calibration are delivered, The team update atmospheric model, convert small force file to acceleration, and update DSN station clock offset and other necessary changes in preparation for the orbit computation. The next step is data editing. Normally this is a fairly simple procedure, but in this case, a good initial condition and good esttmate of the atmosphere density is very important in performing this task, Without the above conditions the data residuals can drift off quickly into hundreds of heltzes. With the atmosphere density varying from orbit to orbit and knowing there is some bad data (large predicted sum of square of residuals), it is difficult to find the bad data. There are times when one orbit of tracking data was deleted at a time in order to find the bad data. Once the data editing is completed, the orbit solution is continue to iterate until convergence. The orbit solution estimates the state vector, Venus gravity field, atmosphere density (every orbit), and contant acceleration (every orbit for thruster firing), The orbit computation is usually finished at between 9:00 to 9:30 am.

The next step is to integrate out a five day trajectory, In this 5 day trajectory, we will be check for the next cotm (corridor orbit trim maneuver) by examining the predicted dynamic pressure at each orbit, Of course the dynamic pressure is a function of the predicted atmosperc density model we use for this trajectory, The atmosphere density model is evaluated daily and update as neccessary. The acceleration from the thruster firing affects the location of cotm. The predicted acceleration must also be evaluated daily and modeled for this 5 day trajectory. If the cotm is within 2-3 days then the cotm must be modeled in the 5 day trajectory. If it is outside 2-3 days then we will keep track of the cotm location by orbit number. The location of cotm may change by 3-4 orbit after detecting it within the 5 day trajectory. It take about 3 iterations of acceleration time for the correct placement of the predicted acceleration at between periapse and 600 seconds after periapses. At the completion of the 5 day trajectory, an OPTG (Orbit Propagation and Timing Generation) file was generated and transfer and release to the Spacecraft Team at 10:30 am, The OPTG file contains orbital event times, Venus centered orbital elements, Venus atmospere density (from input model at periapsis altitude and local solar time) and dynamic pressure.

At this time, the results from the orbit solution, and OPTG are translated into graphic form, When these chart are completed, and many of these chart are generated automatically. These charts are initially discuss at Aerobraking Planning Group meeting at 12:00 pm, This Aerobraking Planning Group consists of a representative from Spacecraft team, Mission Planning Team and Navigation Team. In this meeting, the placement of the COTM, all current problems, future plan and studies are discussed. The recommendation from this group are then presented to the Mission Director at the Mission Director's meeting at 1:30 pm. All the above charts are again presented MD meeting,

At 2:30 pm, another tracking data file was delivered, With another 9 hours of additional tracking an afternoon OD solution was computed to verify that the dynamic pressure is in no detriment to the spacecraft. No 5-day trajectory or products are generated from the afternoon solution until near the end game,

A two week predicted trajectory and OPTG was computed once per week. This predicted trajectory give the aerobraking planning group an advanced look at the frequency of cotm's coming up. On this predicted product, the trajectory is integrated from the current. time to the point when the dynamic pressure limit (0,35 N/m^2) is reached, then a cotm is placed at center of an apoapsis at least 5 hours away from that limit, This procedure continue until a two week duration is attained. Some two week prediction may include as many as 4 cotm's.

Every two weeks, A predicted trajectory and OPTG was computed from the current time to the end of aerobraking. The procedure is the same as the two week predicted trajectory. This predicted trajectory give the aerobraking planning group an advanced look at the plan for aerobraking. Advanced decision such as to push aerobraking harder or slow down to attain a certain spacecraft requirement.

The Aerobraking Results

The two most important challenges for the Magellan Navigation team are to accurately predict the dynamic pressure and the periapsis time. The accurate dynamic pressure will tell us when a cotm must be excuted to keep the spacecraft within the safety margin. The accurate periapsis time will put the spacecraft at the correct attitude during the drag pass to reduce attitude control thruster firing. The dynamic pressure prediction will be discuss first, Figure 4 shows the actual dynamic pressure (using solved for density) picture during the Magellan Aerobraking. The blank triangles are the actual dynamic pressure for each periapsis and the shaded triangles are the 11 rev running mean of the actual values. The actual periapsis altitude are given at the bottom with the occurances of the cotm's. From the extreme left, 0TM3 lowers the periapsis altitude to 149.25 km, and the dynamic pressure was about 0,035 N/m^2, The next 3 walkin cotm's result in dynamic pressure of 0.075 N/m2, 0.15 N/m^2, and 0.23 N/m^2 Magellan aerobraking phase begins with this dynamic pressure. We begin the aerobraking phase using Gerry Keating's double C02 VIRA model for trajectory prediction and the aerobrake baseline. The aerobrake baseline is a complete aerobrake trajectory with all the cotm's needed to stay within the the corridor using the best available inputs at the start of aerobraking. Two days into aerobraking, we concluded that atmosphere density is much closer to the single CO2 VIRA model, and we decided to use the atmosphere model resulting from the solved for values. This model is about 22% above the single CO2 VIRA model, The first aerobrake otm (cot m4) occurs at 4 June 1993 and the upper dynamic pressure limit at this time was 0.32

N/m^2. However, at the time of cotm4 the dynamic pressure was only 0.28 N/m^2. The placement of the cotm was decided too early and too conservative. After this cotm, an re-evaluation of the aerobraking scenerio and with the temperature of the solar panel and high gain antenna is lower then expected, we (APG) concluded that we must be more aggressive and raising the upper dynamic pressure to 0.35-0,36 N/m^2. Without a detailed study, the spacecraft team believed that the upper limit could be higher. Therefore, the cotm 5-11 is executed when the predicted dynamic pressure reachs this upper limit. The predictions of the dynamic pressure for this duration is very accurate as indicted in fig. 4.

Fig. 5 show the periapsis timing error indicated by the Spacecraft Attitude Control error. Fig, 5 shows the navigation periapsis time prediction error and spacecraft attitude error. Majority of the error are the Navigation error and this error is within the 100 sec with a few exception.

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Vira Atmosphere Density Model for f10= 150 : C O 2

ALT	800 hrs		900 firs		1000 hrs		1100 hrs		zoo hrs		1300 hrs		1400 hrs	
	H	RHO	H	RHO	H	RHO	H	RHO	H	RHO	H	RHO	H	RHO
251	18.6	2.50S16	18.8	3.20E-16	19.01	3.59S16	18.65	3.87E-16	18.3	3.41E-16	17.5	2,52S16	17,5J	2.28E-16
246	18.6	3.27E-16	18.8	4.17E-16	19.01	4.67E-16	18.65	5.06E-16	18.32	4.48S16	17.5	3.35S16	17.5	3.03S16
241	18.4	4,29S16	18.6	5.45E-16	18.72	6.10E-16	18.61	6.62%16	18.05	5.91E-16	17.4;	4.46E-16	17.31	4.04%-16
236	18.2	5.64E-16	18.61	7.13S16	18.53	7.99E-16	18.30	8.70E-16	17.8!	7.82E-16	17.3!	5.95X-16	17.34	5.39E-16
231	18,0!	7.44E-16	18.3(	9.37S16	18.30	1.05E-15	17.92	1.15E-15	17.5	1,04%15	17.1	7.96S16	17.1	7.2225-16
226	17.8	9.85'S16	18.3	1.23E-15	18,30	1.38E-15	18.36	1.51E-15	17.6	1.38E-15	16.91	1.07E-15	16.9	9.70E-16
221	17.5	1.31E-15	17,7t	1.63E-15	17.72	1.83E-15	17.48	2.01E-15	17.0	1.85S15	16.8	1.44E-15	16.6	1.31E-15
216	17.6	1,74S15	17.7	2.16E-15	17.63	2,43%15	17.61	2.67E-15	17.0	2.48E-15	16.4	1.95E-15	16.61	1.77E-15
211	16.8	2.34E-15	17.1	2,89S15	17.38	3.24E-15	16,89	3s'9S15	16.4	3.36E-15	16.1	2.66E-15	16.21	2,41S15
206	16.8	3,15S15	16.9;	3.88E-15	16.97	4,35S15	16.74	4.84E-15	16.26	4.57E-15	15.6;	3.66E-15	15.7(	3.31E-15
201	16.1	4.29E-15	16.43	5.26E-15	16.31	5.91S15	16.04	6.61S15	15,6!5	6.29E-15	15.3	5,07S15	15.41	4.58E-15
1.96	15.5	5'.92S15	15.79	7.22E-15	15.80	8.11E-15	15.48	9.13S15	14.9	8.78E-15	14.7	7.12S15	14.8	6.42S15
191	14.9	8.27E-15	14.9	1.01E-14	15.07	1.13E-14	14.80	1.28E-14	14.1	1,25%-14	13.9	1,02S14	14.2	9.13E-15
186	14.0	1.18S14	14.3	1.43E-14	14.12	1.61E-14	13.78	1.84E-14	13.5	1.81E-14	13.1	1.49E-14	13.2	1.33E-14
181	12.8;	1.74E-14	13.1	2.09E-14	13.22	2.35E-14	12.79	2.72S14	12.2	2,72E-14	12.1	2,25"-14	12.4	1.99S14
176	11.9:	2.64E-14	12.1	3.15E-14	12,04	3.56E-14	11.70	4.17E-14	11.2	4.24E-14	11.0	3.54S14	11.2	3.1 OE-14
171	10.7	4.21E-14	10.9	4.97E-14	10.91	5.63S14	10,61	6.68E-14	10.1!	6.94%14	9,92	5.86E-14	10.1	5.08E-14
166	9.57	7.1 O'E-14	9.80	8.28S14	9.79	9.38E-14	9.51	1.13E-13	9.1.3	1.20E-13	8,87	1.03E-13	9.03	8.84E-14
161	8.48	1.28E-13	8.71	1.47E-13	8.76	1.66S13	8,39	2.05E-13	8,07	2,23S13	7.90	1.94E-13	8.01	1.65E-13
156	7.47	2.50E-13	7.72	2,81%13	7,65'	3.19E-13	7,51	3.99E-13	7.21	4.46E-13	7.03	3..95S13	7.09	3.34E-13
151	6.54	5.37E-13	6.79	5.87E-13	6.78	6.67S13	6.60	8.51%13	6.42	9.72E-13	6.26	8.78E-13	6.32	7.37E-13
150	6.02	6.34E-13	6,24	6.89E-13	6.24	7.83E-13	6,20	1.00E-12	5.95	1.15E-12	5.91	1,04S12	5.87	8.74E-13
149	5.86	7.52E-13	6.13	8.11E-13	6.12	9.22S13	5.75	1.19E-12	5.71	1.37E-12	5.69	1.24E-12	5.75	1.04E-12
148	5.71	8.96E-13	5.93	9.60S13	5.97	1.09S12	5.89	1,41S12	5.75	1.63E-12	5.44	1.49E-12	5.69	1.24E-12
147	5.63	1.07E-12	5,82	1.14S12	5,68	1.30S12	5.71	1.68S12	5.58	1,95S12	5.45	1.79E-12	5.44	1.49E-12
146	5.35	1.29E-12	5.44	1.37E-12	5.69	1.55S12	5.43	2.02E-12	5,36	2.35E-12	5..?2	2.16S12	5.29	1.80E-12
145	5.09	1.57E-12	5.56	1.64E-12	5,33	1.87E-12	5,29	2.44E-12	5.18	2,85S12	5.1$	2,62S12	5,10	2.19 E-12
144	5.10	1.91E-12	5.17	1.99E-12	5.28	2.26S12	5.18	2.96E-12	5,08	3.47S12	5.00	3.20E-12	5.05	2.67E-12
143	5,03	2.33S12	5,22	2.41E-12	5,10	2,75E-12	5,04	3.61E-12	4.99	4.24E-12	4.99	3.91E-12	5,01	3,26%-12
142	4.80	2.87S12	5.03	2.94E-12	5.07	3.35E-12	5.00	4.41E-12	4.95	5.19S12	4.88	4.80E-12	4.89	4.00E-12
141	4,83	3.53E-12	4,94	3.60E-12	4,95	4,1OZ12	4.89	5.41E-12	4.84	6.38E-12	4.81	5.91S12	4.83	4.92E-12
140	4.68	4.37E-12	4.87	4.42S12	4.84	5.04E-12	4.78	6.67E-12	4.74	7.88E-12	4.73	7.30E-12	4,76	6.07E-12
139	4.60	5.43E-12	4,82	5.44E-12	4.75	6.22S12	4.73	8.24E-12	4,70	9.75E-12	4.65	9.05'S12	4.67	7.52E-12
138	4.56	6.76E-12	4.73	6.72S12	4.71	7.69E-12	4,69	1.02E-11	4,63	1.21E-11	4,69	1,12S11	4.61	9.34E-12
137	4.46	8.46E-12	4.63	8.34S12	4.64	9.54E-12	4,56	1.27E-11	4.51	1,51%-11	4,48	1.40E-11	4.61	1.16E-11
136	4.43	1.06E-11	4.53	1.04E-11	4.52	1.19E-11	4,45	1.59E-11	4.56	1.88E-11	4.48	1,75S11	4.48	1.45E-11
135	4.41	1.33E-11	4,64	1,2-W-11	4,59	1.48E-11	4,46	1.99E-11	4.40	2,36S11	4.46	2.19E-11	4.40	1.82E-11
134	4.28	1.68E-11	4.39	1.62E-11	4.38	1.86E-11	4,38	2.50E-11	4.41	2.96E-11	4.39	2.75S11	4.44	2.28E-11
l.?.?	4.21	2.13S11	4,43	2.03E-11	4.44	2.33E-11	4.39	3.14E-11	4.38	3.72E-11	4.35	3.46E-11	4.41	2.86E-11
132	4.22	2.70E-11	4.31	2.56E-11	4,30	2.94E-11	4,26	.?.97S11	4,28	4.70E-11	4.33	4.36E-11	4,29	3.61E-11
131	4.13	3.44E-11	4.30	3.23E-11	4.30	3.71E-11	4,26	5.02E-11	4.27	5.94E-11	4.31	5.50E-11	4,32	4.55E-11

TABLE2 Vira Atmosphere Density Mode for f10=150 : C02

ALT	15'00 firs		1600 hrs		1700 hrs		1. 00 hrs		1900 firs		2000 hrs	
	H	RHO	H	RHO	H	RHO	H	RHO	H	RHO	H	RHO
25'1	18.15	2.87S16	18,39	3.04E-16	17.38	1.50E-16	15,9;	3,10S17	21,31	7, 7.%5-18	36.4.9	7.4925-18
246	18.15	3.78E-16	18.39	3,9%-16	17,38	2. 00E-16	15'.9;	4.24E-17	21,31	9.85S18	36.49	8.59E-18
241	18,00	4.99E-16	18.35	5.24S16	17.31	2.67E-16	15.6	5.84S17	19,09	1.28E-17	32.90	1.00E-17
236	17,88	6.60E-16	18.17	6.90E-16	17,38	3.56E-16	15.2	8.1O'E-17	16.92	1.72E-17	28,74	1.19E-17
231	17.66	8.76S16	18.00	9.11E-16	17.09	4,77S16	15.0	1.13E-16	15.40	2.38E-17	24.45	1.46E-17
226	17,28	1.17E-15	17,62	1.21E-15	17.01	6.40E-16	14.9	1.58E-16	14.25	3.38E-17	21.12	1.85S17
221	17,38	1S6S15	17.90	1,60S15	16,79	8.62E-16	14.5	2.23S16	13.39	4,91S17	17,80	2.45S17
216	17.10	2,09S15	17,48	2.1.?S15	16,84	1.16E-15	14.4	3.15X-16	12.74	7.27S17	15.26	3.40S17
211	16.89	2.81E-15	16,97	2.86S15	16.18	1.58E-15	14.2	4.47S16	12.35	1,09S16	13.31	4.95S17
206	16.28	3.82S15	16,82	3.85E-15	16,23	2.15E-15	14.1	6.37S16	11,72	1.67E-16	11.92	7.53E-17
201	16,01	5'.22S15	16,32	5,23S15	15.64	2.96E-15	13,8!	9.14S16	11.60	2,57X-16	10.9.?	1.19E-16
196	15.35	7.23S15	15.85	7,1 7E-15	15.46	4,09S15	13.6(	1.32'S15	11.30	4.00S16	10.12	1,95S16
191	14.96	1.01E-14	15,17	9,97S15	14.83	5.73E-15	13.34	1.92E-15	11,08	6.28E-16	9.67	.?.27S16
186	1.3.83	1.45E-14	14.43	1.41E-14	14.24	8.14E-15	13.0	2.82S15	10.84	9.96S16	9.29	5.60E-16
181	12.85	2.14E-14	13.36	2.05E-14	13.47	1.18S14	12.4	4.21S15	10s'5	1.60E-15	9.02	9.75%16
176	11.88	3.26S14	12.48	3.06E-14	12.51	1.76E-14	11.8	6.42S15	10.30	2.60E-15	8.81	1.72E-15
171	10.66	5.21E-14	11.21	4,78E-14	11,39	2,73E-14	11.0	1. 01E-14	9,80	4,33S15	8,49	3,10'E-15
166	.9,54	8,8(X-14	10,O8	7.85E-14	10,2.3	4.45S14	9.$3	1,68'S14	9,15	7.48S15	8,19	5.71E-15
161	8.45	1,5%-1.3	8.86	1.38E-13	9.01	7,75E-14	8,78	2.97S14	8.26	1.37S14	7.73	1.09E-14
156	7.49	3,1OG13	7,85	2.61E-13	7.89	1.46E-13	7.45	5.81E-14	7.21	2.74E-14	6.94	2.24S14
151	6s'8	6.63E-13	6,86	5.41E-13	6.76	3.06E-13	6.33	1.28E-13	5.96	6.34E-14	5.95	5.19E-14
150	6,11	7.81 E-1.3	6,30	6.34E-13	6,26	3.59E-13	5.61	1.53S13	5.32	7,65S14	5.38	6.25E-14
149	5.95	9.24E-13	6.20	7.45E-13	6,1O	4.23E-13	5,42	1.84E-13	5.09	9.31E-14	5,15	7.59E-14
148	5'.74	1.1 OE-12	5.96	8.81E-13	5',91	5.01E-13	5,33	2.22E-13	4,94	1.14E-13	4,97	9.28E-14
147	5.72	1.31S12	5.70	1.05E-12	5.70	5.97E-13	5.21	2.69%-13	4,70	1.41E-13	4,66	1.15E-13
146	5S2	1,57%12	5,74	1.25E-12	5.50	7.16E-13	4,89	3.30E-13	4,51	1. 76E-13	4.59	1.43E-13
145	5,24	1.90E-12	5.48	1.50S12	5.36	8.63E-13	4,77	4.07E-13	4.39	2.21E-13	4.35	1,80S13
144	5.23	2.30S12	5.17	1,82S12	5.1(J	1.05E-12	4.59	5.06E-13	4.23	2.80E-13	4.23	2.287 S-1-?
143	4,.99	2.81E-12	5,27	2.20E-12	5,05	1.28E-12	4.5'0	6.32E-13	4.07	3.58S13	.3.99	2.93E-13
142	5.02	3.43E-12	5,07	2.68E-12	5,05	1.56E-12	4.36	7.9525-13	3.92	4.62E-13	3.89	3. 79E-13
141	4.94	4.20E-12	4,95	3.28E-12	4,82	1.92E-12	4.18	1,01%12	3.85	5.99E-13	.3.75	4.95E-13
140	4.81	5.17E-12	4.86	4.03E-12	4,75	2.37E-12	4,22	1.28E-12	3.73	7.83E-13	3.65	6.51E-13
139	4,76	6.38E-12	4,82	4.96S12	4.71	2.93E-12	4.14	1.63E-12	3.65	1.03E-12	.3.53	8.64E-13
138	4.71	7.89E-12	4,72	6.13E-12	4,55	3.65E-12	3,95	2.1 OZ-12	3.60	1.36E-12	.3,50	1.15E-12
137	4,61	9.80E-12	4,65	7.60E-12	4.54	4.55E-12	.?,92	2.71E-12	3.50	1,81S12	3.35	1.55E-12
136	4.57	1.22E-11	4.57	9.46%12	4.40	5.71E-12	3.87	3.51S12	3.44	2.42S12	3,29	2,1 O'E-12
135	4.55	1.52E-11	4.52	1.18E-11	4.37	7.18S12	.3,76	4.58S12	3,3.9	3.25E-12	3.24	2.86E-12
134	4.38	1.91E-11	4,41	1.48E-11	4.32	9.05'S12	3,75	5.98E-12	3,35	4.38E-12	3.20	3.91E-12
133	4.46	2.39E-11	4.48	1.85E-11	4.17	1.15E-11	3,68	7.85E-12	.?,32	5,92S12	3.17	5.36S12
132	4,34	3. 01E-11	4,33	2.33E-11	4,31	1.45E-11	.3,68	1.03E-11	3.27	8.04E-12	3.13	7.38E-12
131	4,34	3,79X-11	4,24	2.95E-11	4.10	1.85E-11	3.51	1.37E-11	3.19	1,1 0E-11	3.09	1.02E-11

TABLE 3 THE EXPECTED ORBIT ACCURACY FOR BEGINNING OF AEROBRAKE

ANALYSIS ASSUMPTIONS:

Epoch is 27 May 1993, The MGN04 gravity model, The VIRA atmospheric model

ORBIT ATTRIBUTES:

Periapsis is at 11 am local solar time, Periapsis altitude= 139.46

Apoapsis altitude=8335.845, Orbit period=3.2 hours, Eccentricity=0.3985378

TRACKING DATA SCENARIO:

Eight orbits of two-way Doppler data with two-way minus three-way Doppler data

60 minute data gap centered about periapsis

16 minute data gap centered about apoapsis

PERIAPSIS TIME ERROR (seconds)

	1 DAY	2 DAYS	3 DAYS	4 DAYS	5 DAYS
EST STATE, BIAS ATMOS, 8X8 GRAVITY	0.5	4	18	47	100
RANDOM ATMOSPHERE FLUCTUATIONS (10%)	22	54	95	142	188
AACS THRUSTER FIRING (16 MM/S PER REV)	5	18	41	72	112
OTM (5%)	1	12	36	74	124
RSS (ATM 10%)	22.59	58.31	111.02	181.75	270.67
RSS (ATM 20%0)	44.30	110.22	198.50	305.82	423.43

PERIAPSIS ALTITUDE ERROR (meters)

	1 DAY	2 DAYS	3 DAYS	4 DAYS	5 DAYS
EST STATE, BIAS ATMOS, 8X8 GRAVITY	47	65	99	142	192
OTM (5%)	82	82	83	83	84
RSS	94.51	104.64	129.19	164.48	209.57

2

TABLE 4 THE EXPECTED ORBIT ACCURACY FOR NEAR END OF AEROBRAKE

ANALYSIS ASSUMPTIONS:

Epoch is 13 July 1993, The MGN04 gravity model, The VIRA atmospheric model

ORBIT ATTIBUTES:

Periapsis is at 4 pm local solar time, Periapsis altitude= 136.282 km

Apoapsis altitude=2683.965 km, Orbit period= 1.972 hours, Eccentricity=0.1704067

TRACKING DATA SCENARIO:

Eight orbits of two-way Doppler data with two-way minus three-way Doppler data

60 minute data gap centered about periapsis

16 minute data gap centered about apoapsis

PERIAPSIS TIME ERROR (seconds)

	1 DAY	2 DAYS	3 DAYS	4 DAYS	5 DAYS
EST STATE, BIAS ATMOS, 8X6 GRAVITY	1	5	28	82	204
RANDOM ATMOSPHERE FLUCTUATIONS (10%)	17	70	163	243	333
AACS THRUSTER FIRING (16 MM/S PER REV)	6	22	44	78	121
OTM (5%)	9	34	93	178	305
RSS (ATM 10%)	20.17	81.02	194.78	321.78	510.07
RSS (ATM 20%0)	35.69	145.63	342.99	529.S0	769.96

PERIAPSIS ALTITUDE ERROR (meters)

	1 DAY	2 DAYS	3 DAYS	4 DAYS	5 DAYS
EST STATE, BIAS ATMOS, 8X8 GRAVITY	72	106	226	445	928
OTM (5%)	65	67	133	136	139
RSS	97.00	125.40	262.23	465.32	938.35

TABLE 5 THE EXPECTED ORBIT ACCURACY FOR END OF AEROBRAKE

ANALYSIS ASSUMPTIONS:

Epoch is 26 **July** 1993, **The** MGN04 **gravity model, The** VIRA atmospheric **model**

ORBIT ATTRIBUTES:

Periapsis is at 5pm local solar time, Periapsis altitude = 135.349 km

Apoapsis altitude = 988.858 km, Orbit period = 1.65 hours, Eccentricity= 0.0642629

TRACKING DATA SCENARIO:

Eight orbits of two-way Doppler data with two-way minus three-way Doppler data

60 minute data gap centered about **periapsis**

16 minute data gap centered about **apoapsis**

PERIAPSIS TIME ERROR (seconds)

	1 DAY .	2 DAYS	3 DAYS	4 DAYS	5 DAYS
EST STATE, BIAS ATMOS, 8X6 GRAVITY	3	11	52	173	470
RANDOM ATMOSPHERE FLUCTUATIONS (30%)	**57**	196	*384*	*608*	*924*
AACS THRUSTER FIRING (16 **MM/S PER REV)**	6	22	50	92	152
OTMS (5%)	5	34	109	258	547
RSS **(ATM 30%)**	57.61	200.44	405.64	668.93	1181.94

PERIAPSIS ALTITUDE ERROR (meters)

	1 DAY	2 DAYS	3 DAYS	4 DAYS	5 DAYS
EST STATE, BIAS ATMOS, 8X6 GRAVITY	111	210	382	661	1332
RANDOM ATMOSPHERE FLUCTUATIONS (30%)	23	44	56	112	294
OTMS (5%)	63	131	210	319	630
RSS	129.69	251.39	439.50	742.45	1502.52

FIG 1 ATTITUDE CONTROL THRUSTER FIRING

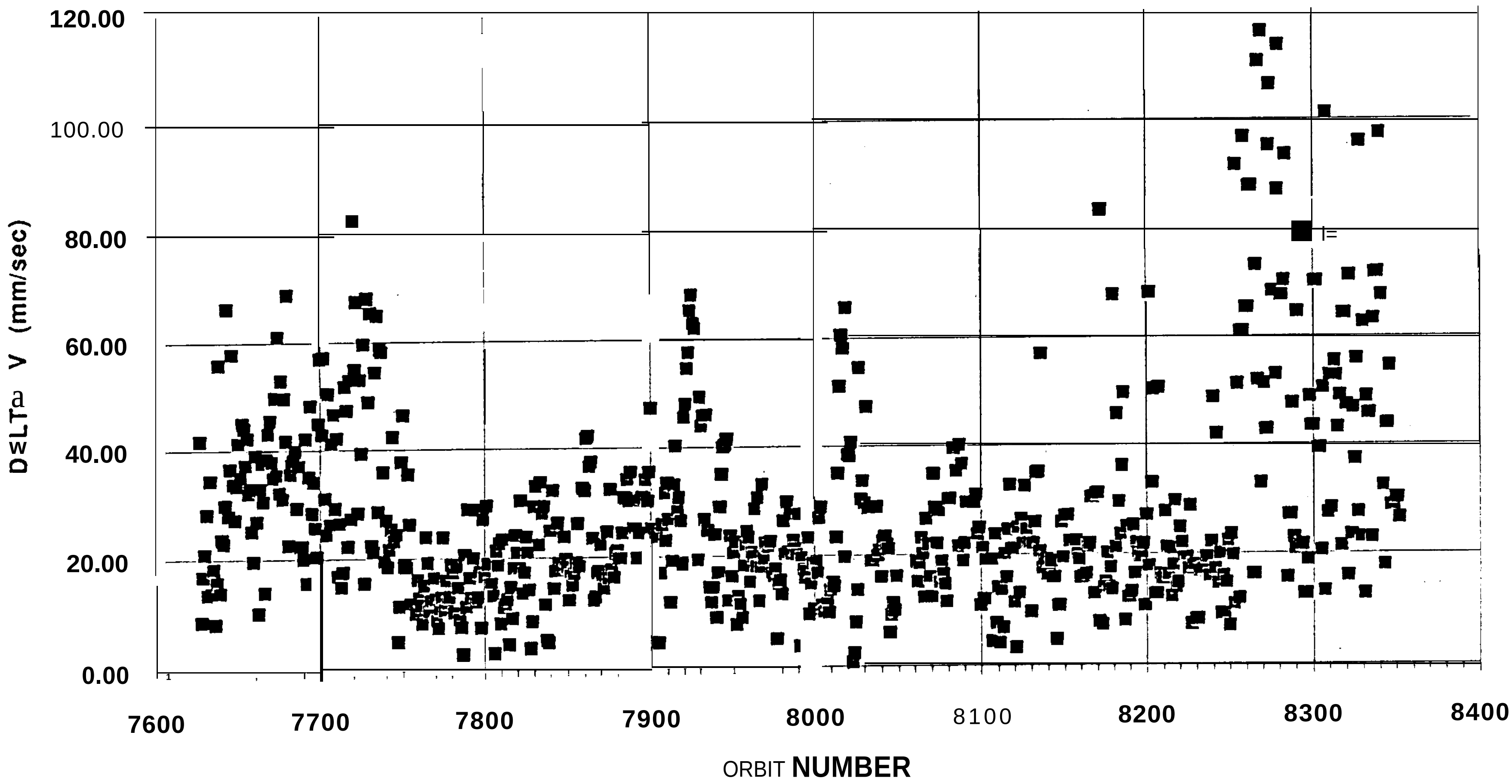
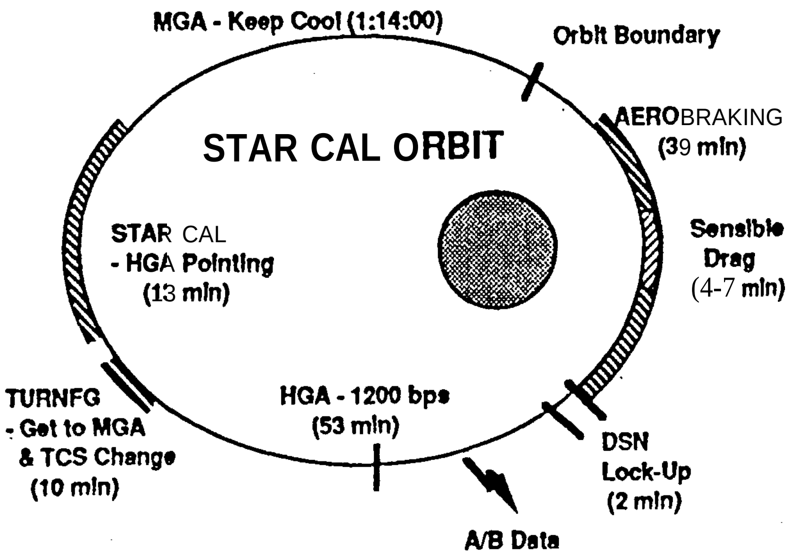


FIG 1

FIG. 2 ORBIT PROFILES - MAIN PHASE

- DAY OF AEROBRAKING 1 THROUGH 60
  (REPRESENTATIVE TIMES SHOWN)



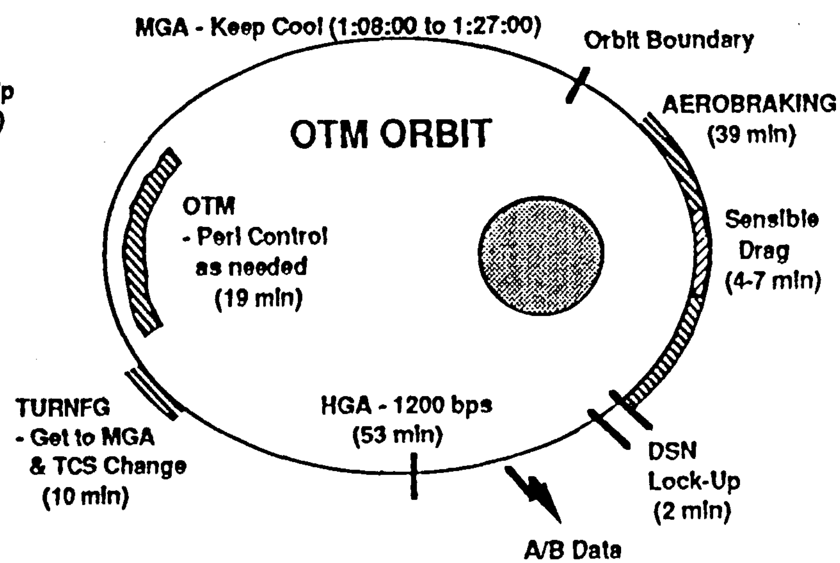
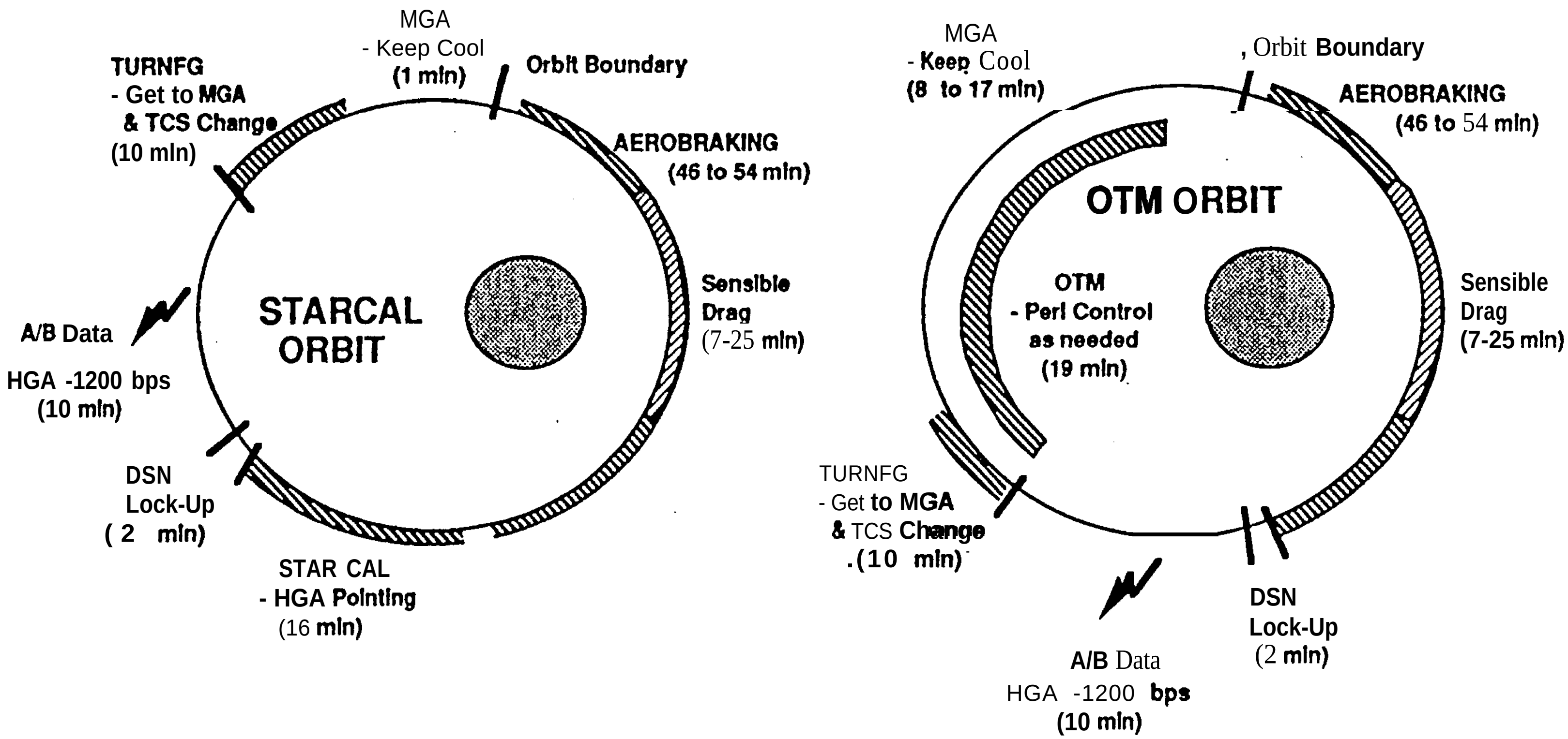


FIG 2

FIG.3 ORBIT PROFILES - END GAME

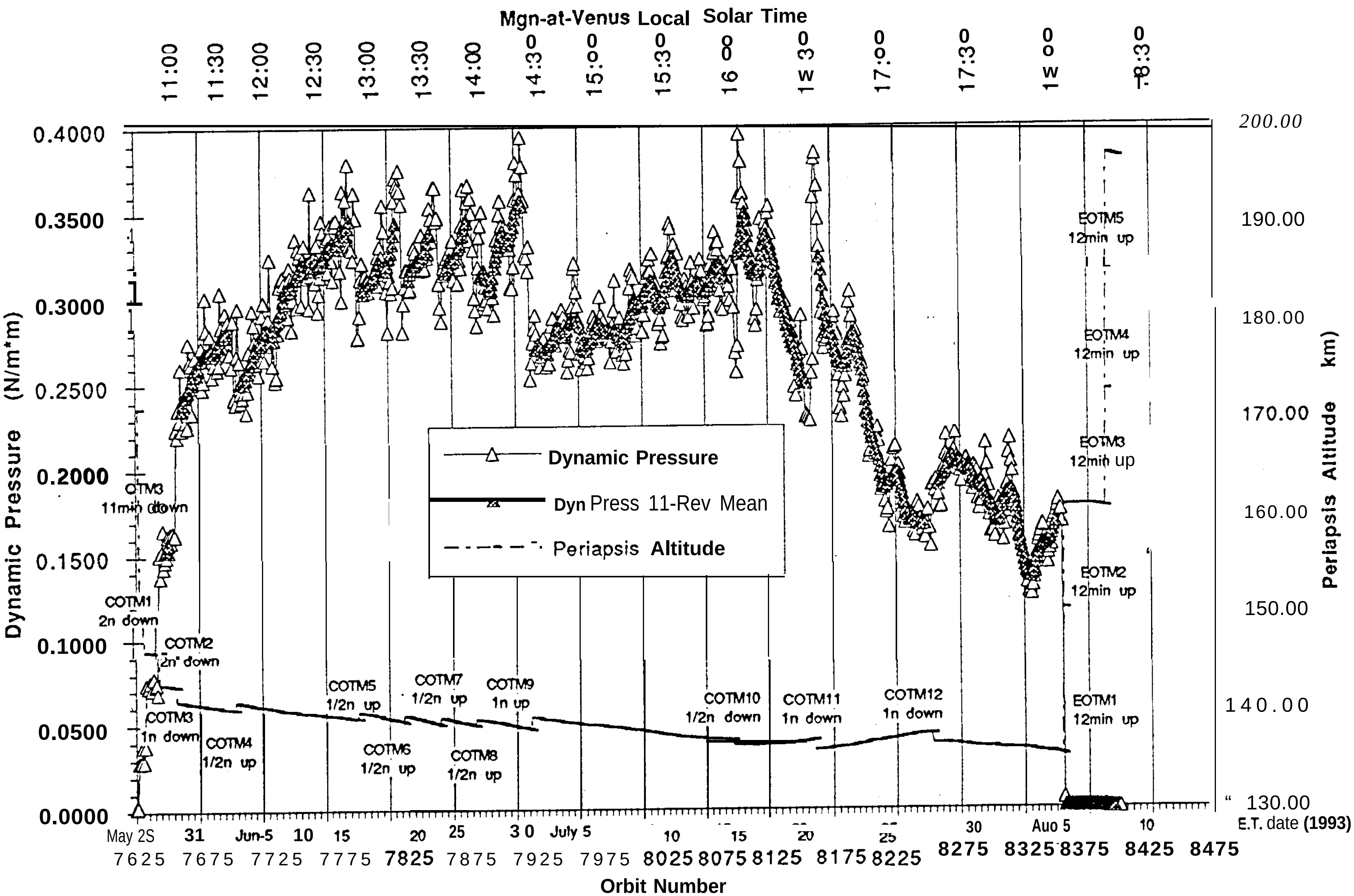
DAY OF AEROBRAKING 60-70



17

FIG 3

FIG.4 **Venus Atmosphere Dynamic Pressures during Magellan Aerobraking**



18

Magellan Navigation 8/31/93 4:11 PM

PERIAPSIS TIMING ERROR

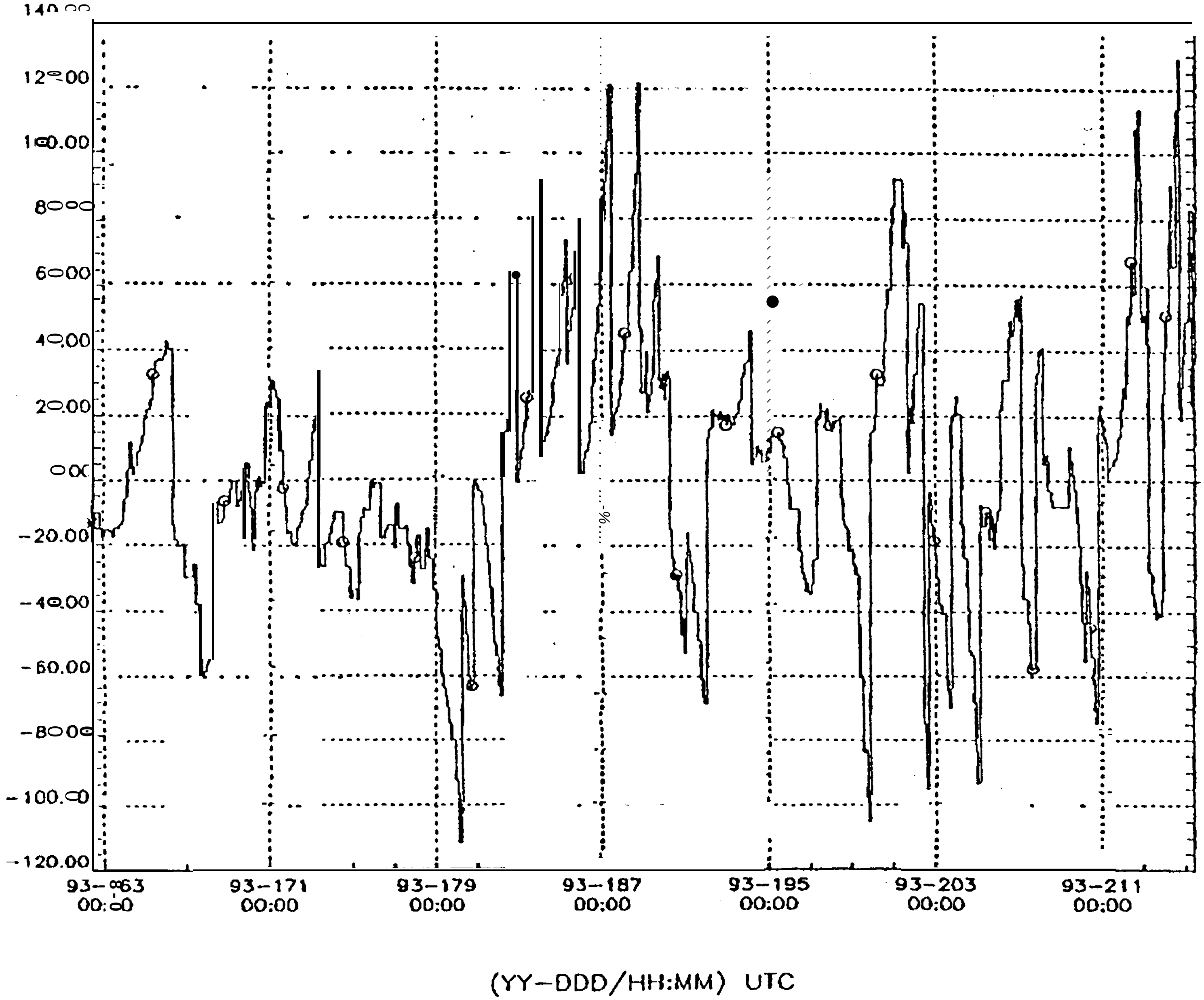
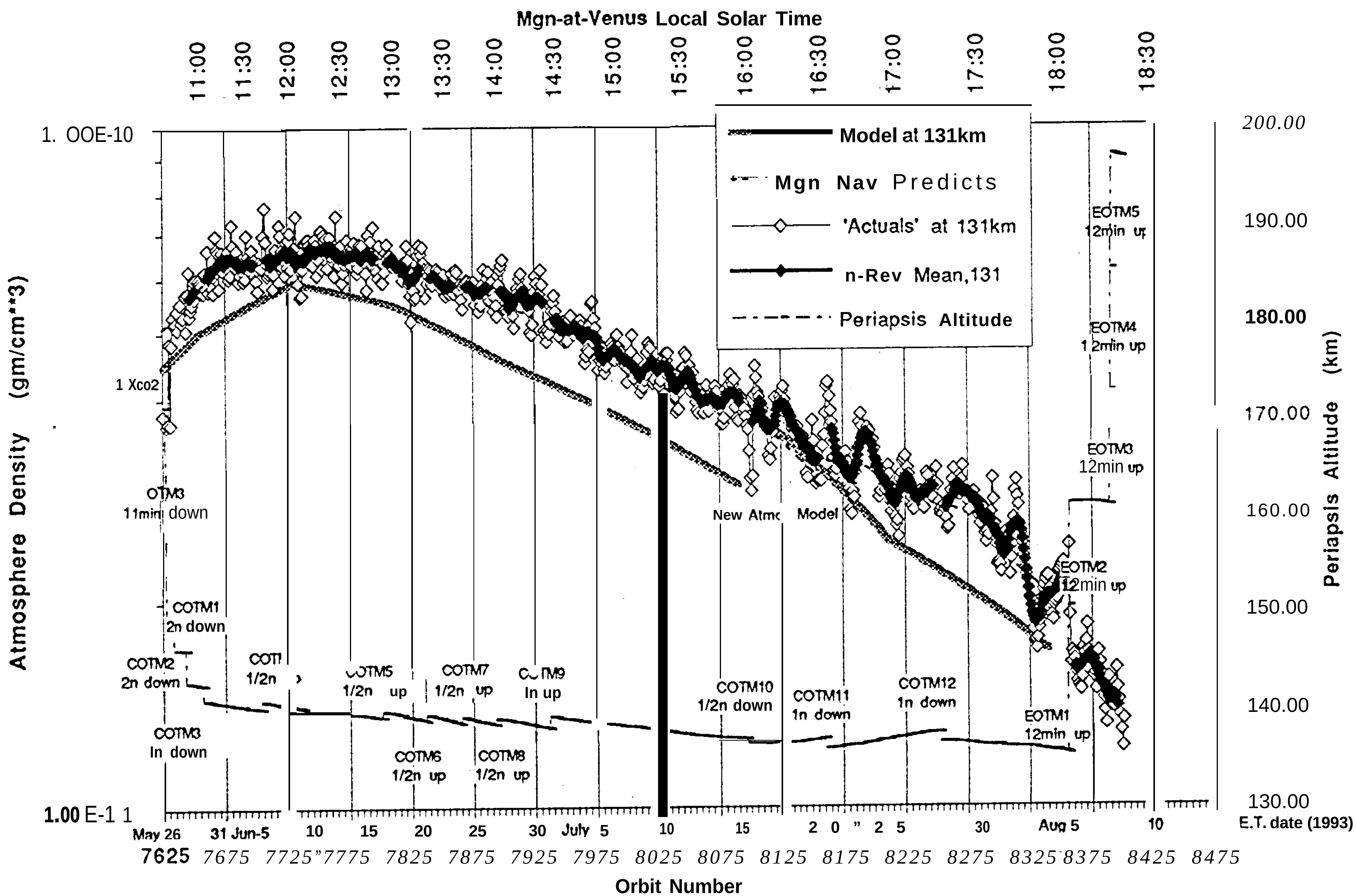


FIG. 5

FIG 6 **Venus Atmosphere Density (scaled to 131 km) during Mgn Aerobraking**



Magellan Navigation 8/31/93 4:29 PM